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Explaining the Flavor Anomalies with a Vector Leptoquark (Moriond 2019 update)

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Several experiments revealed intriguing hints for lepton flavor universality (LFU) violating new physics (NP) in semi-leptonic B meson decays, mainly in $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$ transitions at the $3-5\,\sigma$ level. Leptoquarks (LQ) are prime candidates to address these anomalies as they contribute to semi-leptonic decays already at tree level while effects in other flavor observables, agreeing with the standard model (SM), are loop suppressed.
In these proceedings we review the vector leptoquark $SU(2)_L$ singlet, contained in the famous Pati-Salam model, which is able to address both $b \to c\tau\nu$ and $b \to s\mu^+\mu^-$ data simultaneously. Due to the large couplings to tau leptons needed to account for the $b \to c\tau\nu$ data, sizable loop effects arise which we include in our phenomenological analysis. Updating our result of Ref. [1] with the recent measurements of LHCb [2] and BELLE [3, 4] we find an even better fit to data than before.

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1. Introduction

While so far the LHC has not detected any particles beyond the ones present in the Standard Model (SM), intriguing hints for LFU violation in semi-leptonic B-meson decays were accumulated in several (classes of) observables:

$b \to s\ell^+\ell^-$

In these flavor changing neutral current transitions, measurements of the ratios

$$R(K^{(*)}) = \frac{\mathrm{Br}\left[B \to K\mu^+\mu^-\right]}{\mathrm{Br}\left[B \to Ke^+e^-\right]}$$

show sizable deviations form their respective SM prediction. While the newest measurement of $R(K)$ by the LHCb collaboration [2] shows a deviation of $2.5\,\sigma$ from the SM, the Belle result for $R(K^{(*)})$ is consistent with the SM [3]. However, due to the larger errors, this result also agrees with previous LHCb measurements of $R(K^{(*)})$ which deviate from the SM [5] in the same direction as $R(K)$. Taking into account all other $b \to s\mu^+\mu^-$ observables (like the lepton flavor universal observable P_5' [6]), the global fit prefers various NP scenarios above the $5\,\sigma$ level [7] compared to the SM, also when the newest measurements are taken into account [8–11].

In order to resolve the discrepancy in the neutral current transitions, an effect of $\mathcal{O}(10\%)$ is required at the amplitude level. Since this flavor changing neutral current (FCNC) is suppressed in the SM as it is only induced at one loop level, a small NP contribution is already sufficient. In a global fit one finds a preference for scenarios like $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ (i.e. a left-handed current coupling to muons only) [8]. Such an effect is naturally obtained at tree-level with the vector LQ $SU(2)$ singlet [1, 12–32]. However, a $C_9^{\mu\mu} = -C_{10}^{\mu\mu}$ effect complemented by a flavor universal effect in C_9 gives an even better fit to data [8, 33]. As we will see, this is exactly the pattern that arises in our model.

$b \to c\tau\nu$

There are also indications for LFU violation in charged current transitions, namely in the ratios

$$R(D^{(*)}) = \frac{\mathrm{Br}\left[B \to D^{(*)}\tau\nu\right]}{\mathrm{Br}\left[B \to D^{(*)}\ell\nu\right]}$$

where $\ell = \{e, \mu\}$. While the newest measurements from Belle [4] agree with the SM prediction, including previous measurements by BaBar, Belle and LHCb still yield a deviation of $3.1\,\sigma$ [34] from the SM prediction. Furthermore there is also a measurement of the ratio $R(J/\Psi) = \frac{\mathrm{Br}[B_c \to J/\Psi\tau\nu]}{\mathrm{Br}[B_c \to J/\Psi\mu\nu]}$ exceeding its SM prediction [35].

Also here a NP effect of $\mathcal{O}(10\%)$ is needed at the amplitude level. However, since $b \to c\tau\nu$ transitions are mediated at tree level by the exchange of a W boson in the SM, the NP effect needs to be large. This means that NP should contribute at tree level with sizable couplings and at a not too high NP scale. Here, the best single particle solution is the vector LQ $SU(2)$ singlet [1, 12–32] since it does not give a tree-level effect in $b \to s\nu\nu$ processes and provides a common rescaling of $R(D)$ and $R(D^*)$ with respect to the SM prediction.

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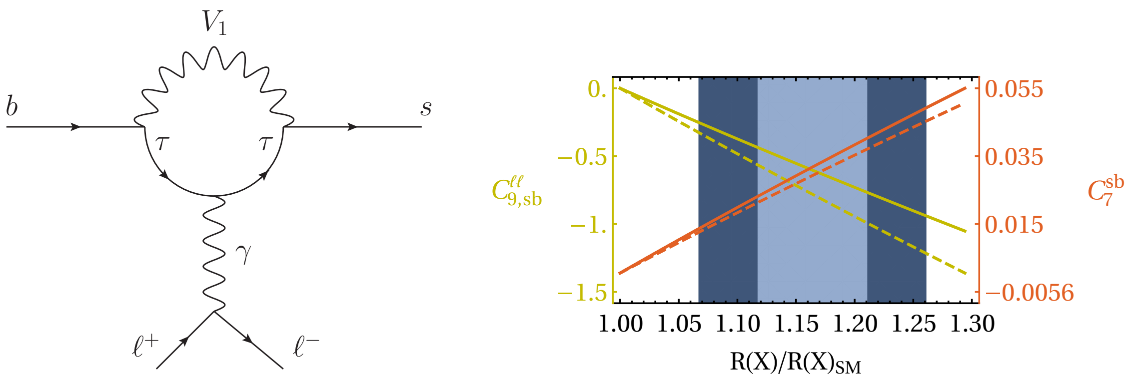

Figure 1: Left: Feynman diagram depicting the loop effects induced by the $bc\tau\nu$ operator from $SU(2)$ invariance. Right: $C_{9,sb}^{\ell\ell}$ and $C_7^{sb}(\mu_b)$, generated by these loop effects, as functions of $R(D^{(*)})/R(D^{(*)})_{\rm SM}$. The solid (dashed) lines correspond to $M = 1$ TeV (5 TeV) while the (dark) blue region is preferred by $b \to c\tau\nu$ data at the $1\,\sigma$ $(2\,\sigma)$ level, taking into account the most recent measurements. From the global fit, taking into account only lepton flavor conserving observables, we have $-1.29 < C_{9,sb}^{\ell\ell} < -0.87$ [38] and $-0.01 < C_7^{sb}(\mu_b) < 0.05$ [7] at the $1\,\sigma$ level. Assuming an explanation of $b \to c\tau\nu$, our model predicts the right size and sign of the effect in $C_{9,sb}^{\ell\ell}$ and $C_7^{sb}(\mu_b)$ needed to explain $b \to s\ell^+\ell^-$ data.

2. The Pati Salam vector leptoquark as combined solution to the anomalies

The vector Leptoquark $SU(2)_L$ singlet with hypercharge $-4/3$, arising in the famous Pati-Salam model [36], is a prime candidate to explain both the anomalies in charged current and neutral current B decays simultaneously [12–14, 17–20]. It gives a $C_9 = -C_{10}$ effect in $b \to s\ell^+\ell^-$ at tree level and at the same time a sizable effect in $b \to c\tau\nu$ without violating bounds from $b \to s\nu\nu$ and/or direct searches and does not lead to proton decay. Note that this LQ by itself is not UV complete, however several UV complete models for this LQ have been proposed [15, 16, 21–29, 37].

For the purpose of our phenomenological analysis, let us consider a model where we simply extend the SM by this LQ. Its interaction with the SM particles is given by the Lagrangian

$$\mathscr{L}_{V_1} = \kappa_{fi}^L \overline{Q_f} \gamma_\mu L_i V_\mu^{1^\dagger} + h.c.\,,$$

where $Q(L)$ is the quark (lepton) $SU(2)_L$ doublet, κ_{fi}^L represents the couplings of the LQ to the left handed quarks (leptons) and f and i are flavor indices. Note that in principle couplings to right-handed SM particles are also allowed, they are however not relevant for this discussion. After electro-weak symmetry breaking, we work in the down basis, meaning that no CKM matrix elements appear in FCNC processes.

We start by taking κ_{23}^L and κ_{33}^L as the only non-zero couplings, as they are necessary to explain $b \to c\tau\nu$ data. Here, strong effects in $b \to s\tau^+\tau^-$ transitions [39] are generated which at the 1-loop level affect $b \to s\ell^+\ell^-$ via the Wilson coefficients $C_{9,sb}^{\ell\ell}$ and C_7^{sb}, as is depicted to the left in Fig. 1. Due to the correlation with $b \to c\tau\nu$, these Wilson coefficients can be expressed as functions of $R(D^{(*)})/R(D^{(*)})_{\rm SM}$. The Wilson coefficients' dependency on these ratios is shown in the right plot of Fig. 1, where the RGE evolution of C_7^{sb} from the NP scale down to the b quark scale is also taken into account (see Ref. [40]). Interestingly, assuming an explanation of $b \to c\tau\nu$ data, the effects

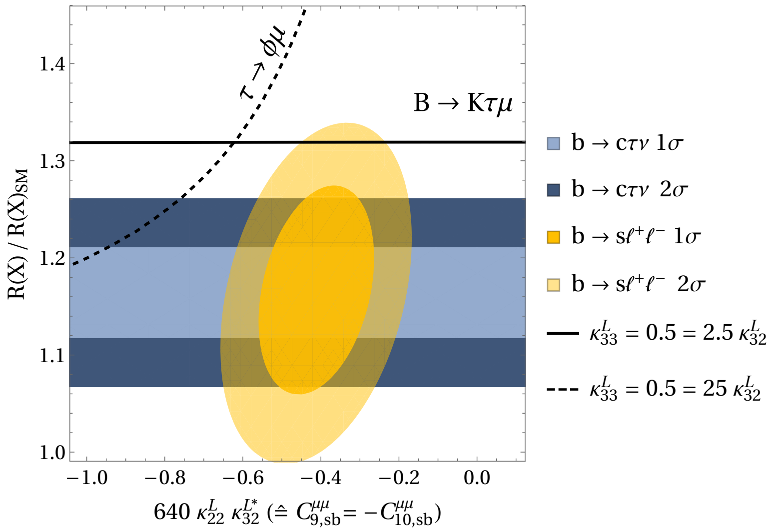

Figure 2: Allowed (colored) regions in the $C^{\mu\mu}_{9,sb} = -C^{\mu\mu}_{10,sb}$ $(\equiv 640\kappa^L_{22}\kappa^{L*}_{32}) - R(X)/R(X)_{\rm SM}$ plane for $M = 1$ TeV and $X = \{D, D^*\}$ at the $1\,\sigma$ and $2\,\sigma$ level. The region above the black dashed (solid) line is excluded by $\tau \to \phi\mu$ $(B \to K\tau\mu)$) for $\kappa^L_{33} = 0.5 = 25\kappa^L_{32}$ $(\kappa^L_{33} = 0.5 = 2.5\kappa^L_{32})$. The bound from $\tau \to \phi\mu$ $(B \to K\tau\mu)$ depends on κ^L_{33} and κ^L_{32} and gets stronger if κ^L_{32} gets smaller (larger). That is, for $\kappa^L_{33} = 0.5$ and $2.7 \lessapprox \kappa^L_{33}/\kappa^L_{32} \lessapprox 27$, the whole $2\,\sigma$ region preferred by $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$ data is consistent with these bounds. Note that we used the most recent experimental results for both the $b \to c\tau\nu$ and $b \to s\ell^+\ell^-$ transitions, therefore updating our analysis in Ref. [40].

generated in $C^{\ell\ell}_{9,sb}$ and C^{sb}_7 agree with the $1\,\sigma$ ranges of the model independent fit to $b \to s\mu^+\mu^-$ data excluding LFU violating observables [38, 41].

Now we also allow κ^L_{32} and κ^L_{22} to be non-zero, generating a tree level effect in $b \to s\mu^+\mu^-$ which is necessary to account for the LFU violating observables as well. In Fig. 2 we show the allowed (colored) regions from $b \to s\mu^+\mu^-$ and $b \to c\tau\nu$ as well as the exclusions from $b \to s\tau\mu$ and $\tau \to \phi\mu$. A simultaneous explanation of the anomalies is perfectly possible since the colored regions overlap and do not extend to the parameter space excluded by $b \to s\tau\mu$ and $\tau \to \phi\mu$. Interestingly, we predict a lepton flavor universal effect in $C^{\ell\ell}_{9,sb}$ and C^{sb}_7 in addition to a LFU violating tree-level effect of the form $C^{\mu\mu}_{9,sb} = -C^{\mu\mu}_{10,sb}$ in muonic channels only. This means that the effect of NP compared to the SM is expected to be larger in lepton flavor universal observables like $P5'$ relative to LFU violation observables as $R(K^{(*)})$, which is in perfect agreement with global fit scenarios [8]. In fact, the agreement is even better after the inclusion of the new measurements of BELLE and LHCb.

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